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DESIGN OF A FOUR THROW RECIPROCATING COMPRESSOR FRAME FOR NATURAL GAS

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ABSTRACT

A reciprocating compressor is a mechanical device that is used to increase the pressure of a gas by reducing its volume. Compressed natural gas (CNG) is a fuel, which can be used in place of gasoline, diesel fuel and propane/LPG. CNG combustion produces fewer undesirable gases than the aforementioned fuels. As the norms of environmental law are becoming strict and there is increase in number of vehicles which use natural gas as fuel, CNG demand has risen by more than 50% in recent years but supply is not sufficient. Hence there is need of increasing the capacity of CNG stations. Existing CNG stations use two throw reciprocating compressors. By using four throw compressors, capacity of these CNG stations will increase from 1200 SCMH (Standard Cubic Meter/Hr.) to 2400 SCMH.

In this paper, Design of frame of a four throw reciprocating compressor for natural gas has been presented. Various loads like rod loads, inertia loads etc. are taken into account.

KEYWORDS: Compressor Frame, Rod Loads, Inertia Loads & Frame Load

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Original Article

1. INTRODUCTION

A reciprocating compressor or piston compressor is a positive displacement compressor that uses pistons driven by a crankshaft to deliver gases at high pressure.

The reciprocating compressor consists of pistons, cylinders, connecting rods, piston rods, crankshaft, valves, frame etc. The primary components of a typical reciprocating compressor system are shown in figure 1.

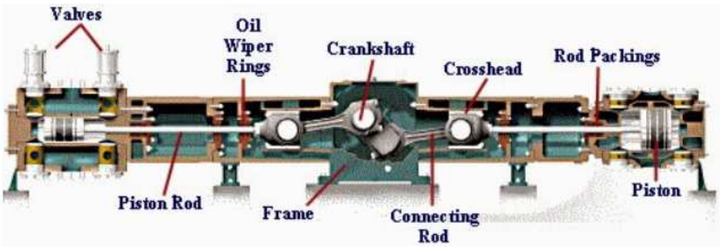

Figure 1: Basic Parts of Reciprocating Compressor

The cylinder end, which is nearer to the crank is called crank end and the other end is called head end. Out of which, first stage is double acting ad other two stages are single acting.

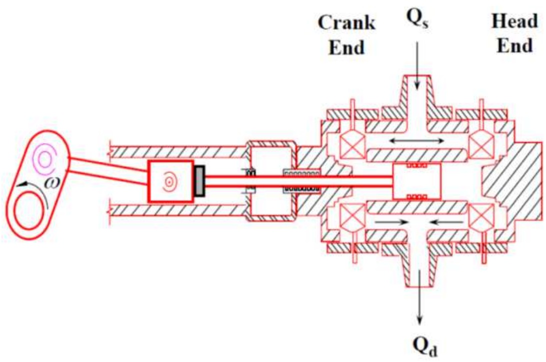

Figure 2: Double-Acting Compressor Cylinder

In this case, we have 3 stage 4 throw compressor. The first stage is double acting and second stage and third stage are single acting. The exhaust of first stage is provided as the input gas for second stage and exhaust of second stage is provided as input gas for third stage. In second stage, gas will be compressed at crank end and at head end we will provide one dead valve to avoid vacuum pressure at that end. In third stage, gas will be compressed at head end and we will provide dead valve to avoid the vacuum pressure.

The proposed arrangement of the cylinders & other parts is as shown in the figure 3.

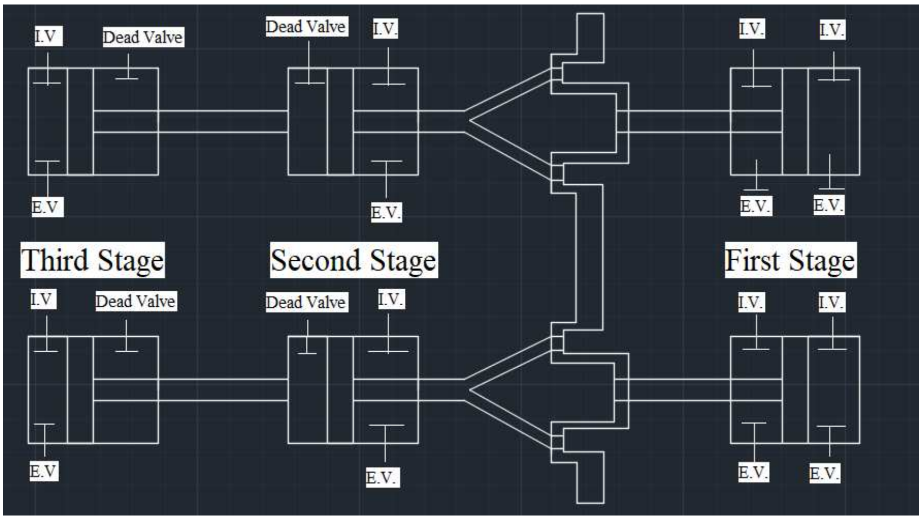

Figure 3: Arrangement of Various Elements of Four Throw Compressor

2. LOADS ACTING ON THE FRAME OF A RECIPROCATING COMPRESSOR

The total load acting on the frame of the compressor comprises of gas loads & piston rod loads.[1]

2.1. Gas Loads

As the compressor piston moves to compress gas, the differential pressures acting on the piston and stationary components result in gas forces. The pressures acting on the piston faces i.e. both on head end and crank end result in forces on the piston rod. The forces due to pressure also act (equal and opposite) on the stationary components.

$$F_{Tension} = (P_{Discharge} X A_{CE}) - (P_{suction} X\ A_{HE}) \quad (1)$$

$$F_{Compression} = (P_{Discharge} X\ A_{CE}) - (P_{Suction} X A_{HE}) \quad (2)$$

2.2. Piston Rod Loads

The actual rod load is defined as the force due to the differential pressure across the piston plus the inertia of the reciprocating parts, transmitted through the piston rod.[2]

Piston rod load is nothing but the forces acting on the piston rod due to the two differential pressures acting on head end and crank end piston areas *plus* the inertia forces due to the reciprocating mass.

The reciprocating inertial force can be computed using the following equation.

$$F_I = M_{recip}(\cos \omega t + \frac{r}{l}\cos 2\omega t)$$

Where,

M_{recip}= mass of reciprocating components

r = crank radius

ω = angular velocity, &

l = connecting rod length

t = instantaneous time

Total Force acting on the frame = Gas force + Inertia Force

3. DESIGN OF 4 THROW COMPRESSOR FRAME

Design inputs are as given in Table 1.

Table 1: Design Inputs

Sr. No	Description	Symbol	Unit	Value
1	Length of connecting rod	L	mm	215.9
2	Stroke	l	mm	76.2
3	Crank Radius	r	mm	38.1
4	L/R Ration	n		5.67
5	Compressor Speer (RPM)	RPM	N	1800
6	Average Piston Speed			9.14
7	Angular Speed	rad/sec	Ω	188.50
8	Diameter of Ist stage cyl	d_1	Mm	120.650
9	Diameter of IIst stage cyl	d_2	Mm	85.725
10	Diameter of IIIst stage cyl	d_3	Mm	44.450
11	Diameter of piston rod	d	Mm	28.575
12	Pressure at head end (Ist Cylinder)	P_{HE}	N/mm^2	5.5
13	Pressure at crank end (Ist Cylinder)	P_{CE}	N/mm^2	1.9
14	Pressure at head end (IInd Cylinder)	P_{HE}	N/mm^2	5.5
15	Pressure at crank end (IInd Cylinder)	P_{CE}	N/mm^2	12.5
16	Pressure at crank end (IIIrd Cylinder)	P_{CE}	N/mm^2	12.5
17	Pressure at head end (IIIrd Cylinder)	P_{HE}	N/mm^2	25

3.1. Proposed Frame Model

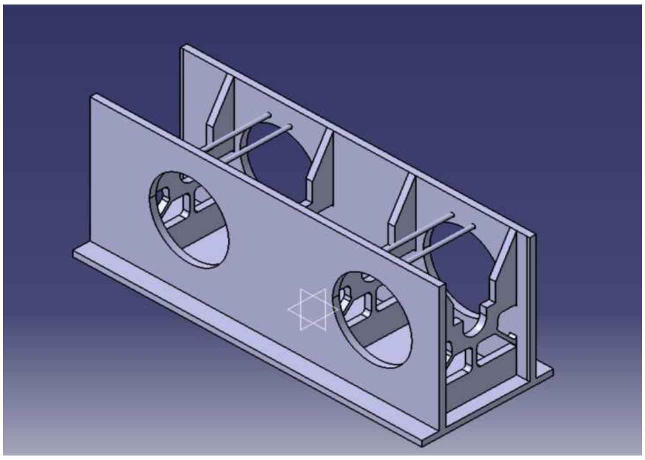

Figure 4: Frame of 4 Throw Compressor (Proposed)

3.2. Load Calculations

3.2.1. Force due to Pressure

Ist Stage

$$Fp = P_{HE} X A_P - P_{CE} X (A_P - A_{ROD})$$

$$= 5.5 X \frac{\pi}{4} X 120.65^2 - 1.9 X \frac{\pi}{4} X (120.65^2 - 28.575^2)$$

$$= 42375.79\, N$$

IInd Stage

$$Fp = P_{HE} X (A_P - A_{ROD}) - P_{CE} X (A_P - A_{ROD})$$

$$= 12.5 X \frac{\pi}{4} X (85.725^2 - 28.575^2) - 5.5 X \frac{\pi}{4} X (85.725^2 - 28.575^2)$$

$$= 35912.89\, N$$

IIIrd Stage

$$Fp = P_{CE} X (A_P - A_{ROD}) - P_{HE} X (A_P)$$

$$= 12.5 X \frac{\pi}{4} X (44.45^2 - 28.575^2) - 12.5 X \frac{\pi}{4} X (44.45^2)$$

$$= -8016.27\, N$$

$$Total\ Force\ due\ to\ Pressure = 42375.79 + 35912.89 - 8016.27$$

$$= 70272.41 N$$

3.2.2. Force due to Inertia

$$F_I = mr\omega^2 (\cos \omega t + \frac{r}{l} \cos 2\omega t)$$

Where,

$m = \ reciprocating\ mass$

$\omega = \ angular\ accelaration$

$\mathrm{m} = \ Reciprocating\ masses$

$m = \ mass\ of\ piston + mass\ of\ piston\ rod + mass\ of\ crosshead +$

$reciprocating\ mass\ of\ connecting\ rod + mass\ of\ wrist\ pin + Balancing\ masses$

Table 2: Masses of Reciprocating Components

	I[st] Throw	II[nd] Throw
Mass of Piston	9.5254	6.714
Mass of Piston rod	2.65	2.65
Mass of crosshead	4.7	4.682
Mass of Connecting rod	11.736	11.764
Reciprocating mass of connecting rod	3.7555	3.7645
Mass of wrist pin	3.032	3.032
Balancing mass	N/A	2.8014

Reciprocating Mass of connecting rod = (1/3) X mass of connecting rod [3]

For I[st] Throw

$m = 9.5254 + 2.65 + 4.7 + 3.7555 + 3.032$

$m = \ 23.6630\ kg$

$F_I = 23.6630\ \mathrm{X}0.0381\mathrm{X}188.50^2\ (\cos 0 + \frac{0.2159}{0.0381}\cos 0)$

$= 37685.7040\ N$

For II[nd] Throw

$m = 6.714 + 2.65 + 4.682 + 3.7645 + 3.032 + 2.8014$

$m = \ 23.6439\ kg$

$F_I = 23.6439\ \mathrm{X}0.0381\mathrm{X}188.50^2\ (\cos 0 + \frac{0.2159}{0.0381}\cos 0)$

$= 37655.3807\ N$

Force on Frame

Total Force on frame = Gas Load + Inertia Force

$= 70272.4101 + 37685.7040 + 37655.3807$

$= 146513.4947\ N$

3.2.3. Load Factor

The forces acting on the bearing are calculated by considering the equilibrium of forces in vertical and horizontal planes. These elementary equations do not take into consideration the effect of dynamic load. The forces determined by these equations are multiplied by a load factor to determine the dynamic load carrying capacity of the bearing.

Table 3: Load Factor for Dynamic Loads [4]

Types of Drive	Load Factor
(A) Gear drives	
I. Rotating machines free from impact like electric motors and turbo-compressors	1.2-1.4
II. Reciprocating machines like internal combustion engines and compressors	1.4-1.7
III. Impact machines like hammer mills	2.5-3.5
(B) Belt Drives	
I. V-belts	2.0
II. Single-ply leather belts	3.0
III. Double-ply leather belts	3.5
(C) Chain Drives	1.5

$\text{Total Force on Frame} = \text{Actual load} X \text{Load factor}$

$= 145613.4948 \text{ X } 1.7$

$= 247542.9409\ N$

$\text{Load on support} = 247542.9409/2$

$= 123771.4705\ N$

3.2.4. Material Selection for Frame

The material for frame of compressor is taken as Ductile Iron (Cast iron) ASTM A536 Gr 60-40-18.[5]

Table 4: Properties of Ductile Iron (Cast Iron) as per ASTM A536 Gr 60-40-18

Physical Properties	
Density	7.10-7.20 g/cc
Mechanical Properties	
Hardness, Brinell	143-187
Ultimate Tensile Strength	≥ 414 MPa
Yield Tensile Strength	≥ 276 MPa
Elongation at Break	18%
Component %	
Carbon	≥ 3%
Iron	94%
Phosphorous	≤ 0.080%
Silicon	≤ 2.5%

3.2.5. Thickness of Frame Wall

Yield Stress of Ductile Iron = 276 MPa

$$Permissible\ Stress = \frac{Actual\ Stress}{Factor\ of\ Safety}$$

$$Permissible\ Stress = \frac{276}{3} = 92\ MPa$$

$$Stress = \frac{Force}{Area}$$

$$92 = \frac{123771.4705}{(39.624+25.4) X\ t}$$

$$t = 20.69\ mm$$

3.2.6. Tie Rod Design

$$M = \frac{\pi}{32} \text{X } Tesnsile\ Stress\ \text{X} d^3 \quad (3)$$

Where,

$M = Bending\ Moment$

$d = Diameter\ of\ tie\ rod$

$M = Load\ \text{X}\ L$

$= (\text{weight of connecting rod} + \text{weight of piston} + \text{weight of crosshead pin} + \text{weight of crosshead} + \text{Wieght of wrist pin} * 143.002$

$= \ 310.4218 * 143.002$

$= 44390.94\ Nmm$

From Equation (1)

$44390.94 = \frac{\pi}{32} \text{X} \frac{414}{3} \text{X} d^3$

$d^3 = 3276.54$

$d = 14.85\ mm$

4. CONCLUSIONS

Load acting on 4 throw natural gas reciprocating compressor frame are calculated in this paper. The calculation of wall thickness of frame is also carried out. But, due to reciprocating components and fluids in frame, some internal pressure is also being induced in the frame. Hence, it is necessary to design the frame with consideration of internal pressure.

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